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A review of occupant control on natural ventilation

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ABSTRACT

According to IPCC (Intergovernmental Panel on Climate Change), the largest use of energy in commercial buildings is space heating in colder climates and air conditioning in hot climates. In Europe, the Directive on the energy performance of buildings EPBD (European Energy Performance of Buildings Directive) [1] provides a framework for national building performance regulations and calculation procedures. However, there are often large discrepancies between calculated and measured energy performance of buildings. One main reason is the behaviour of occupants, which is often not reflected in calculation models.

This paper presents a literature review of various parameters influencing the effectiveness of occupant controlled natural ventilation. Additionally possibilities to implement these influences into calculation procedures/building simulation and adaptive thermal comfort evaluation are discussed.

Contents

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1. Introduction

The worldwide energy consumption has increased dramatically within the last century. Related atmospheric greenhouse gas emissions are responsible for the climate change which is becoming more and more perceptible. In order to prevent a further acceleration, immediate action is required and according to the Fourth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) [2] the buildings sector has the greatest potential for climate change mitigation (Fig. 1).

According to IPCC, the largest use of energy in commercial buildings is space heating in colder climates and air conditioning in hot climates. Both are aimed to provide satisfying thermal comfort at the occupant's workplaces.

In the Kyoto protocol, all participating states have agreed to fulfil their national obligations to mitigate greenhouse gas emissions. Regarding the building sector, building regulations to limit the energy consumption for heating, cooling and lighting have been developed. On European level, the Directive on the energy performance of buildings [1] is providing the framework of requirements which are currently transposed into national legislation. These national norms provide a methodology to calculate energy efficiency of buildings, minimum requirements as well as a method for evaluation or classification of the results.

However, there are often large discrepancies between the calculated or simulated energy performance according to national legislation and measured energy performance in real buildings. One main reason for these deviations might be the use of typical standard values for various parameters in the calculation procedure. These parameters are aimed to achieve comparability of calculation results among different buildings. But at the same time they exclude the individuality of the specific building and its occupants. Many recent field studies focused on the influence of occupant behaviour on energy performance and comfort in office buildings. And the results lead to the conclusion, that occupant behaviour might be one main reason for the differences between calculated and real energy performance and comfort in buildings.

Occupants influence thermal and visual comfort as well as energy performance by various parameters. One main parameter of occupant behaviour is the control of natural ventilation. Openable windows link the indoor thermal environment to outside climatic conditions, and the resulting thermal comfort can be considered as a product of the outside climate, building properties and the behaviour of occupants.

Based on a literature review, this paper investigates the influence of occupant behaviour on natural ventilation. Additionally possibilities to better reflect individual characteristics of climate, specific buildings as well as user behaviour in building simulation and energy performance calculation procedures are discussed.

2. Climate

2.1. Climate change and heat waves

Natural ventilation is a direct link between the climate and indoor thermal comfort. Windows are opened to let fresh air into the room or, and if outside temperature allows to avoid increase of room air temperatures or to cool the room. The effectiveness of natural ventilation therefore depends to a large extent on the difference between outside and room air temperatures.

Since greenhouse gas emissions within 1970 and 2004 have increased by 70% (IPCC) causing an already perceivable increase of temperatures as well, projections of the Intergovernmental Panel on Climate Change for the 21st century predict an even stronger effect, resulting in a warming of about 0.2 °C per decade for the next two decades [3]. This implies that during warm summer days, when the differences between outside and room temperature are usually smaller anyway, a further increase in outside air temperatures will decrease the effectiveness of thermally driven ventilation. This will have negative effect on thermal comfort in offices, and might lead to a vicious circle of equipping office buildings with increasingly powerful air conditioning systems which are contributing to an acceleration of the climate change due to increasing energy consumption for cooling. To avoid this effect it seems necessary to have a closer look at climate characteristics, in order to derive possible strategies to maintain thermal comfort in offices without further increase in energy consumption. Especially after recent heat waves (e.g. European heat wave in 2003), the question how to face similar extreme climate events in future has become important.

Although there is no universal definition of a heat wave, it can be described as unusually high atmosphere-related heat stress, which causes temporary modifications in lifestyle and has notable

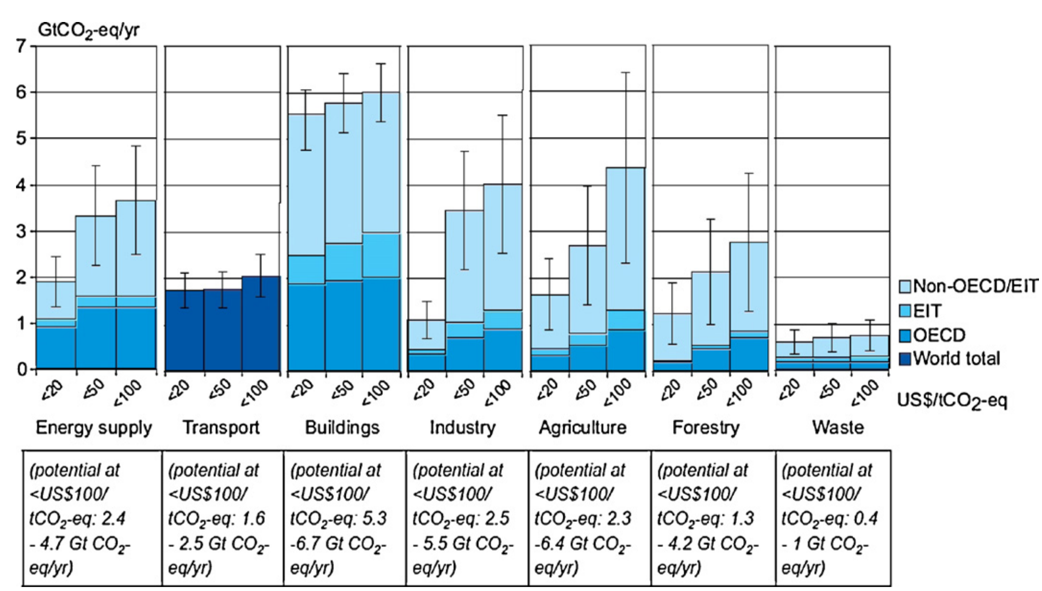


Fig. 1. Estimated economic mitigation potential by sector and region using technologies and practices expected to be available in 2030. The potentials do not include non-technical options such as lifestyle changes. *Source*: IPCC [2].

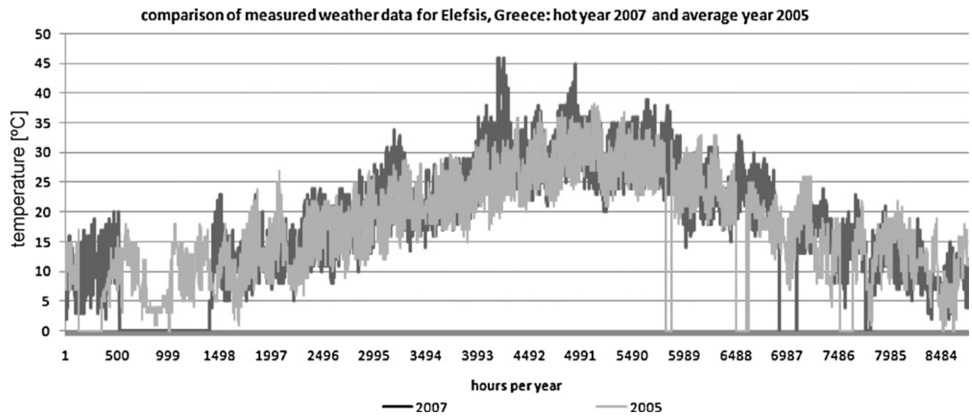


Fig. 2. Measured outside air temperatures at Elefsis Airport, Greece for year 2007 (hot, incl. heat waves) and year 2005 (average). However, in 2007 heat waves accounted for only ~5% of the working days.

impacts on health and human mortality, as well as regional economies, and ecosystems [4–6]. When evaluating the influence of climate change on thermal comfort, the impact of heat waves should not be neglected. Based on a global coupled climate model, Meehl and Tebaldi [6] examined future behaviour of heat waves for different climate scenarios. They predicted for a future warmer climate with increased mean temperatures, that heat waves would become more intense, longer lasting, and/or more frequent. Figs. 2 and 3 illustrate exemplary for the climate in Elefsis, Greece, the magnitude of heat waves in a hot year 2007 compared to the average year 2005.

Especially in hot climates during heat waves in summer, outside air temperatures can be expected which are significantly exceeding the room air temperatures. During these periods, there is no effectiveness to natural ventilation, and opening a window will even increase room air temperatures. During those heat waves it will therefore be difficult if not impossible to maintain satisfying thermal comfort in offices without using an additional cooling system. For this reason many buildings in hot climates are, although naturally ventilated during a part of the year, additionally equipped with an air conditioning system (mixed mode). The dimension of these systems is often chosen according to expected peak cooling loads, which occur typically during heat waves. However, heat waves typically occur only during very short periods of the year, presumably only about 5% of the working days.

As observed by de Dear and White [7] for the climate of Sydney, the electricity demand peaks during heat waves due to the use of air conditioning. But increasing the grid capacity to meet those peak load demands for cooling would represent an inefficient use of resources, since heat waves only occur during very short periods. For this reason it is necessary to investigate other solutions to decrease energy consumption during heat waves.

2.2. Inner city microclimate

As far as office buildings are concerned, the most attractive locations are usually in the heart of a city. Although modern communication technologies decrease the dependency of a workplace from a specific location, these inner city locations are often preferred due to reasons of prestige, and/or better connections to public transport.

In this context the heat island effect should be considered, because it can significantly alter the local climate to a different urban microclimate. According to Mihalakakou et al. [8] the intensity of heat islands is not constant. There are periodic and non-periodic fluctuations depending on weather conditions, topographic and topoclimatic complexities and synoptic flow patterns. Geros et al. [9] showed in a field study in different urban canyons in central Athens, that climatic conditions inside and outside an urban canyon are frequently different. According to their investigation, the local microclimate in an urban canyon is strongly related to the form and the geometry of the canyon, its orientation, the heat sources and the construction materials. In the investigated canyons the daily amplitude of the air temperature was higher outside an urban canyon than inside. This was found to be due to the geometry of the canyons, which reduces the penetration of solar radiation during the daytime period. During the night period, the air temperature outside the canyon was lower than that measured inside. The long wave radiation exchanges during the night between the surfaces of the canyon obstruct the "release" of heat, which is stored in the construction materials in daytime. The resulting average difference between the temperature inside and outside the canyons during the night varied up to 3 °C. In the same canyons the measured wind velocity decreased significantly inside the canyons compared to outside the canyon

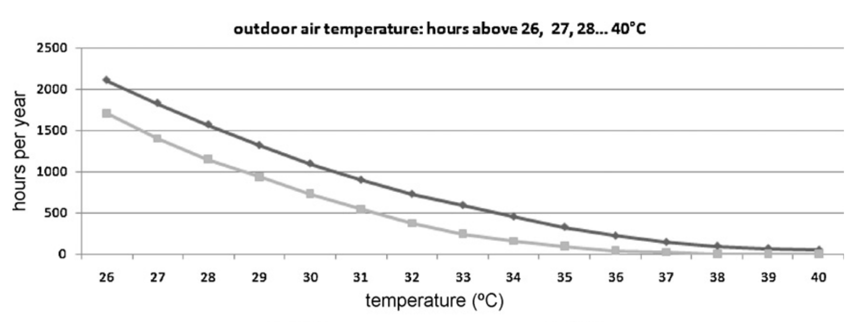


Fig. 3. Comparison of outside air exceeding hours above 26–40 for the measured hot year 2007 and the average year 2005 at Elefsis Airport, Athens, Greece.

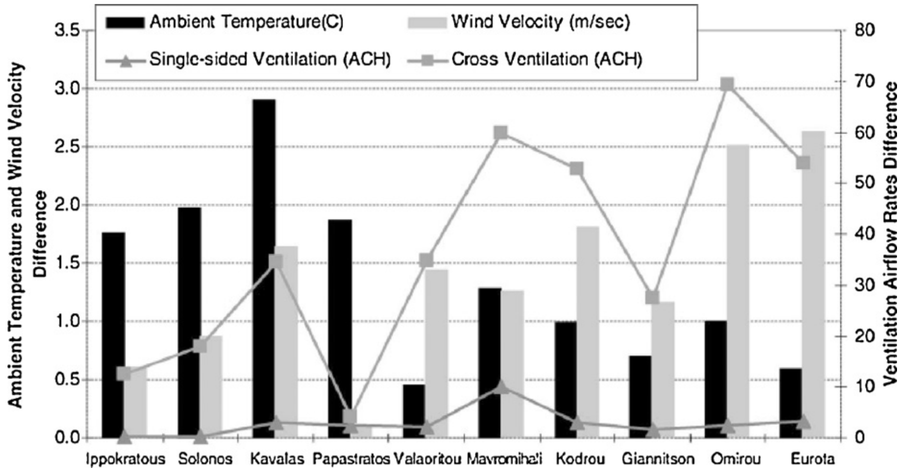


Fig. 4. The average difference of the ambient temperature, the wind velocity (horizontal component) and the ventilation airflow rate between the two locations of the typical zone, when ventilation is single-sided and cross. *Source*: Geros et al. [9].

with variations up to 2.6 m/s and wind direction varying up to opposite direction.

As differences between outside and room air temperature as well as wind speed and direction are key drivers for air exchange, the resulting air exchange rates for single sided ventilation varied according to their field study from 0.2 to 10 1/h and from 4 to 69 for a room with cross-ventilation. As illustrated in Fig. 4 for different urban canyons in Athens, Greece, the heat island effect can have strong impact on air exchanges and resulting thermal comfort and energy consumption in office buildings.

2.3. Wind and rain

Another climate parameter which has influence on occupant controlled ventilation is the occurrence of wind and rain. Generally it can be assumed, that windows are usually opened either to let fresh air into the room and thus improve the room air quality, or they are opened for cooling. Both reasons are dominated by internal parameters of the room, however more or less influenced by the difference between room and outside air temperature. But there are some occasions, when influences from the outside of the building become predominant concerning ventilation control by occupants. These are the occurrence of wind and rain (snow etc.). Concerning wind, occupants are likely to close the windows despite a wish for fresh air or cooling, if the sensation of draft in the office is producing a predominant discomfort. This likelihood is strongly depending on wind direction, and generally increased at higher wind speeds. However, as shown above, wind speed and direction can change significantly in a dense urban environment. Precise predictions will therefore be difficult. The occurrence of rain can be another reason for office occupants to close the windows, to avoid rain entering the room. But this aspect is closely related to window type, opening percentage, overhangs, as well as wind direction. Some window types and opening angles provide better rain protection than others. In combination with overhangs some windows might be well protected, so ventilation can be maintained during rainfall. Additionally, the occurrence of wind can put one facade at more risk for rain intrusion than another.

3. Façade design

Although room geometries and thermal mass play an important role as well, the effectiveness of natural ventilation is strongly depending on properties of ventilation openings and their controllability. This aspect is closely related to façade design. And the behaviour of occupants can be considered as a reaction to the controls provided by the specific design.

Although there is not much literature available on the subject, two main aspects of façade design influencing ventilation could be derived. One is the choice of the window opening type and the second is the size and placement of the openings within the façade.

3.1. Window opening type and opening percentages/angles

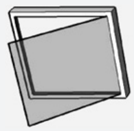
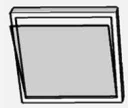
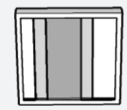
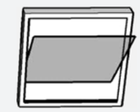
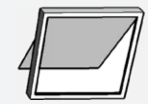
There is a large variety of window opening types available. Different window opening types have different properties regarding weather protection, maximum achievable ventilation rates, adjustability of opening sizes and possible interferences of opened windows with furniture. The choice which one will be applied in an office building is mainly an architectural decision which is strongly influenced by the climate. In moderate climates, window types might be preferred which provide a good weather/rain protection in opened state, e.g. bottom hung windows. In warm climates in contrast, the effective opening size and the adjustability might be more important than protection from weather/rain. Generally, the choice of window opening types can be essential for the resulting air exchange rates as well as for the resulting user behaviour. Some window opening types can be adjusted either stepless or in several steps like for example sliding-, pivoted-, side- or top hung windows. Others, e.g. bottom hung windows in contrast are typically either opened to a fixed angle or closed. Table 1 provides an overview on the properties of different window opening types.

Therefore it can be assumed that opening properties predefine the related window opening behaviour. This also affects most behavioural models for window openings, as they typically predict whether a window is opened or closed, but provide no information on window types and possible opening angles/sizes. Nevertheless field studies [10,11] indicate that as long as window design allows, occupants take advantage of continuous window opening adjustment possibilities. Fig. 5 shows the use of different window opening angles in relation to ambient temperature.

Richter et al. [12] investigated temperature driven energetic efficient air exchanges for a naturally ventilated two-person office room using airflow simulation. The results indicate that air exchange rates can multiply according to window opening type, opening angle as well as size and placement within the façade.

These findings agree with Karava et al. [13] who reviewed discharge coefficients for different openings and also reported variability due to window opening type, geometry of openings, pressure differences across the building envelope and wind angle.

Table 1
Evaluation of different window opening types regarding properties affecting the effectiveness of ventilation in offices for typical opening angles. Description of symbols: –, poor; O, medium; +, good.

Properties of different window types when opened at a typical angle	Side hung, opening to inside	Bottom hung, opening to inside	Sliding, opened pane always covers part of window	Horizontal pivoted, lower part opening to outside	Top hung, opening to outside
					
Weather protection	–	+	–	O	O
Max. achievable ventilation rate	+	–	O	+	O
Adjustability of opening size	+	–	+	+	+
Flexibility for placement of furniture	–	+	+	O	+

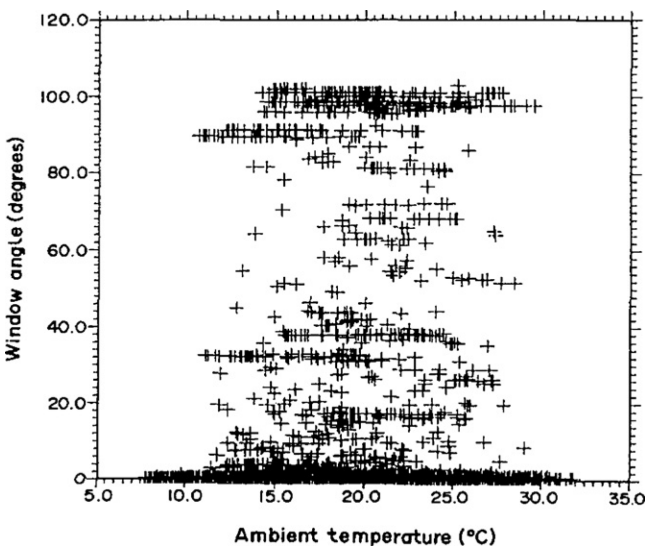


Fig. 5. Bi-parametric graph: window angle vs. ambient temperature (summer 1984, room HIT-west). *Source*: Fritsch et al. [10].

This also corresponds with Baturin [14], indicating a dependency of discharge coefficients from window opening angle.

The detailed geometrical influence of different window opening types on airflow and air exchanges in the room can only be modelled using airflow simulations, e.g. CFD. Due to the complexity of these simulations, they are not likely to be conducted in early design stages. Therefore more detailed information would be needed regarding discharge coefficients for different window opening types, angels/percentages and resulting air exchange rates for different room geometries.

As stated by Karava et al. [13] the use of typical constant discharge coefficient values for building simulation might be a source of error.

3.2. Window size, shape and placement

Although the influence of façade design on the effectiveness of natural ventilation might need further investigation, some publications indicate that size and placement of ventilation openings provide a significant optimization potential for air exchange rates.

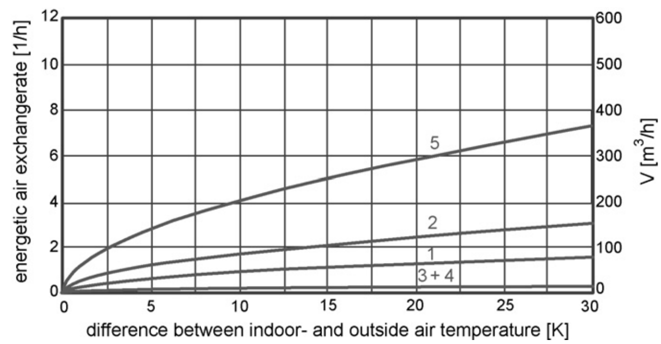


Fig. 7. Energetic air exchange depending on the difference of room- and outside air temperature for the façade design configurations (bottom hung windows) in Fig. 6 according to Richter et al. [12].

Richter et al. [12] compared different window opening configurations for the façade of a typical two-person cellular office room (Fig. 6) and simulated the resulting air exchange rates (Fig. 7). The results show, that size and placement of windows within the façade has significant influence on ventilation rates.

Although further research would be needed it might be concluded that the distribution of the total opening size of a façade on several carefully placed windows can increase the flexibility for different airflow patterns and air exchange rates. This effect can be supported by using adjustable window opening types. All those optimization possibilities are a matter of façade design, but they can increase the perceived user control and ventilation effectiveness.

Hall [15] investigated the effectiveness of ventilation for bottom hung windows in a typical office room and reported a strong dependency of air exchange rates from temperature difference between room- and outside air temperature, wind speed and direction, window size and placement within the façade, depth of window reveal, positioning of heating devices, window decoration (plants, curtains) and user behaviour.

Additionally, according to findings of Tsangrassoulis et al. [16], the influence of different activated shading devices on discharge

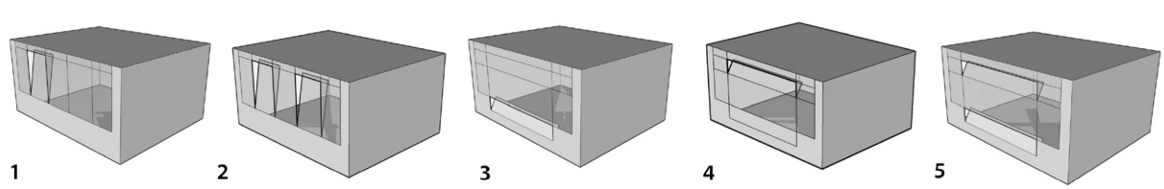


Fig. 6. Façade design configurations 1–5 according to Richter et al. [12] for a typical office room.

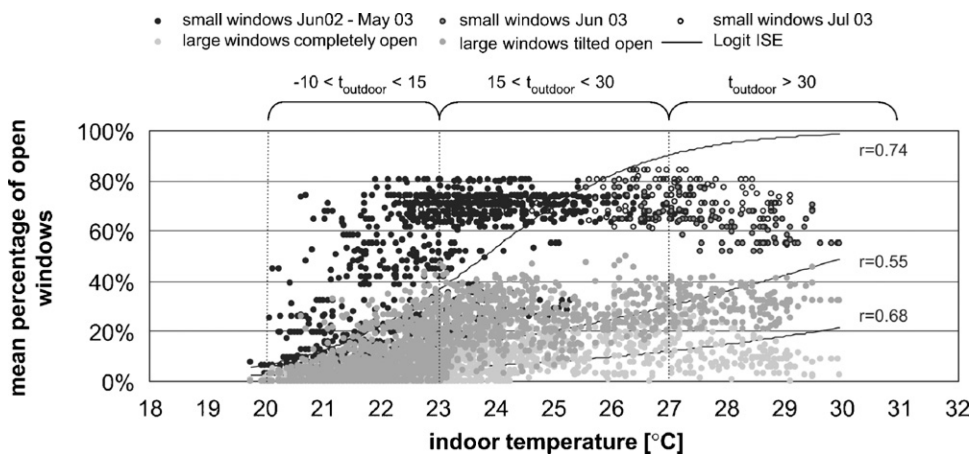


Fig. 8. Correlation of the mean percentage of open windows to the indoor temperature over the period of 13 months (July 2002–July 2003). Hourly mean values. Data evaluation of working hours (weekdays, 8 am–6 pm CET). *Source*: Herkel et al. [17].

coefficients of windows should not be neglected. This implies again direct influence on façade design, because not all window opening types can effectively be combined with all types of switchable shading devices. For example a top hung window (opening to the outside) can be combined with all types of internal blinds. But the combination with external shadings, e.g. a venetian blind, would require an additional external structure to fix it, leaving a gap to the window so it can be opened without affecting the blind.

Herkel et al. [17] conducted a field study on window opening behaviour in a naturally ventilated building in Germany, with a façade consisting of larger tilt and turn windows above sill height and bottom hung clerestory windows in the upper part of the room. The related user behaviour showed slight differences for the different window types, with the clerestory windows being opened less frequently and remaining opened longer than the larger windows (Fig. 8). Additionally the clerestory windows were often used for night ventilation while the larger windows were mostly closed during the night. At higher outdoor temperatures above 20 °C, occupants seemed to prefer opening the small windows more than the larger ones. These differences in user behaviour for different openings within the façade might be due to related different airflow patterns and resulting draft sensation [18] of the occupants. This corresponds to the findings of Spindler et al. [19], also indicating that window opening behaviour is influenced by the perceived air speed at the workplaces.

4. Occupant behaviour for window opening

Several field studies have been conducted to investigate occupant behaviour for window opening. These field studies were conducted in different countries/climates, and had different settings and focus. They differed regarding observation periods (winter, summer, full year, short term, long term), office type (single occupancy, shared office), as well as window type and façade design. Additionally the surveys focused on different correlation variables and different dependencies were found. However, some general parameters influencing occupant controlled ventilation could be derived from the literature.

4.1. Season

Several field studies have been conducted in different climates, to find out correlations of window opening behaviour with environmental parameters. The results generally show a strong correlation of window opening behaviour according to season. For naturally ventilated buildings it was found out that the percentage of windows open is lowest in winter, highest in summer and intermediate in autumn and spring [17,20–23]. Additionally a changing frequency of window openings according to season could be observed. The highest frequency in changing the window opening status was noticed in spring and autumn, and a low frequency in summer because then the windows stay open for longer periods.

4.2. Temperatures

According to the literature review, a main key driver for window switching behaviour in summer is room temperature [11,21–25]. In contrast to outside air temperature it considers the effect of varying internal heat loads and solar heat gains (façade orientation) in different offices. Nevertheless outdoor temperature seems to be an important key driver as well [10,17,21–23,25,26]. An example for window opening behaviour depending on indoor and outdoor temperature is shown in Fig. 9.

These field studies lead to the conclusion that the influence of outside air temperature is varying according to season. Rijal et al. [22] concluded that indoor temperature might be the key driver for window opening, in order to limit the rise of room air temperature. But the question how long the window would remain open would be likely to depend on outdoor temperature. This assumption correlates with Fritsch et al. [10] who assumed that in summer people open the windows in attempt to cool the rooms, while during mid season windows might act as a more convenient heater control than thermostatic valves.

During winter several field studies [10,17,24,25] reveal, possibly due to relatively constant heating temperatures, either no significant correlation between window switching and room temperature or that the correlation with outdoor temperature was stronger.

Additionally findings of Yun and Steemers [11,24] indicate that the frequency of window opening events increased with higher indoor temperatures on arrival. This also supports their observation that opening frequency is highest if windows were closed, medium for narrowly opened and low for wide open windows during the night. With time of the day Rijal et al. [23] observed a gradually increasing proportion of windows open, and they concluded this to be a reaction to rising temperatures towards the afternoon. From a field study in Pakistan they also concluded that the proportion of windows open continues to increase in higher indoor temperatures but it decreases in highest outdoor temperatures in order to prevent the hot air entering [22].

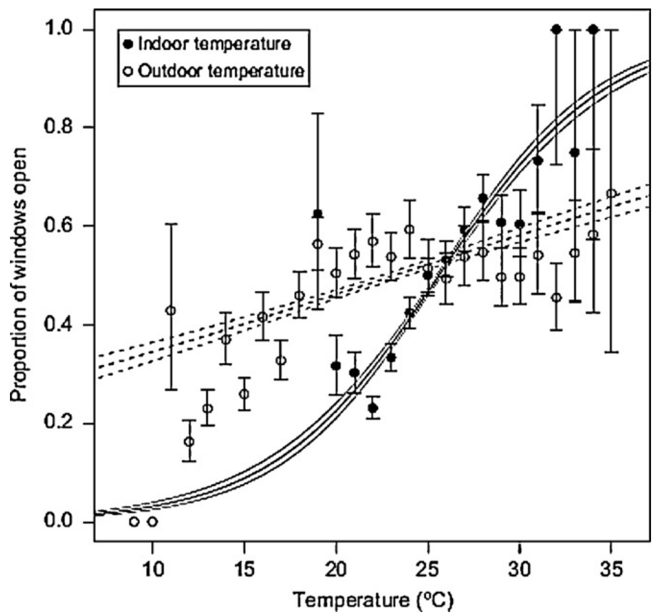


Fig. 9. Window opening probability as a function of indoor and outdoor temperature. *Source*: Haldi and Robinson [25].

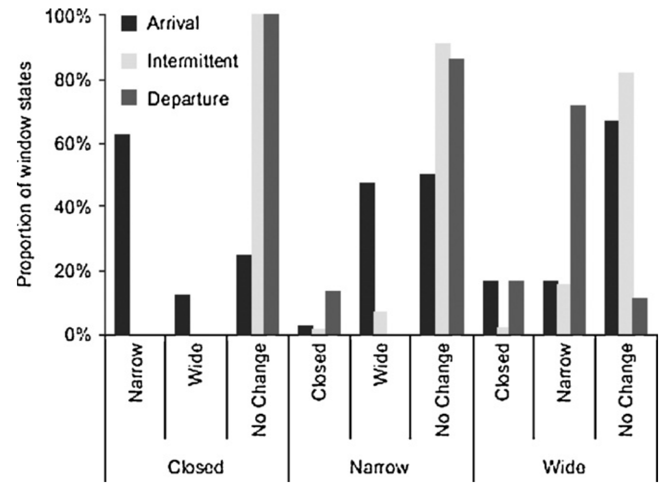


Fig. 10. The proportion of the events of changing a window state at arrival, intermittent period and departure in an office with night ventilation. *Source*: Yun and Steemers [24].

4.3. Time of the day

Regarding the influence of occupancy there was a broad range of individual occupant behaviour observed in field studies in different offices even under similar conditions. Nevertheless some general trends could be derived. Many field studies observed that window control activities mostly occur on arrival of the occupants [11,17,24,27]. For buildings where night ventilation is not possible, this effect might be explained by higher indoor temperatures in the morning, especially in summer. Although the dependency of window switching from indoor air quality might need further investigation, another reason might be that people arriving at work might experience a contrast in perceived air quality when entering the comparably "sticky" office after being more or less exposed to wind and fresh outside air on their way to work. The strength of this contrast might be depending on the possibility for night ventilation, but also on the intensity of indoor air pollutants in the room.

Additionally field studies show, that intermediate window switching during the day is relatively low (Fig. 10), so windows are usually left in the same position for long periods of time [10,11,21,24]. This effect might be partly explained with the fact that occupants might have already adapted to the indoor air quality in the room during this period and the positive effect of opening a window is not perceived as strong as in the morning. Additionally in shared offices, window switching might be perceived controversial by colleagues in intermittent periods, while in the morning there might be a higher general acceptance for opening a window. It might be concluded that "no change" is the 'lowest common denominator' in shared offices.

Another influence regarding the occupant's window switching is the question how windows are operated when there are more occupants then openable windows. It can be important to understand the decision process among occupants for opening the window within an office room. Apart from physical variables like temperatures also social variables might be important in this context.

4.4. Previous window state

Another parameter influencing the window opening behaviour of occupants as observed by field studies [10,24,25] is the previous window state. This parameter was found especially important in the context of night ventilation. If night ventilation is not possible, the previous window state at arrival of occupants in the morning is 'closed'. This means that in summer during the night the room temperature might have increased and the indoor air quality decreased. Both might cause occupants to open the window at the beginning of the day. At the end of the day, in offices without night ventilation the previous window state 'open' will cause subjects to close the window. However, in intermittent periods the windows are controls for natural ventilation, and the window state will be most likely to be changed if discomfort occurs.

4.5. Night ventilation

The literature review of field studies shows that typically either all offices in a building use night ventilation or all windows of the building are kept closed during the nights. Additionally little information is provided about occupant behaviour for night ventilation. Nevertheless there seems to be a strong dependency of night ventilation on façade design and security issues [11]. They also noticed a tendency of occupants changing the window state to closed or slightly open before departure.

Generally it can be assumed that in naturally ventilated office buildings a common security policy might be the reason whether or not night ventilation is applied. And this security policy might be based on the façade design of the building as well as on terms and conditions of insurance companies. For example a room on the ground floor or at another easily accessible geometrical situation might need better burglary protection than a room on a higher floor level. And the size and placement of openings within the façade might also be important to prevent burglary. Additionally the influence of weather protection during the absence of occupants can be a reason to close the windows during the night.

Therefore the architect's influence on the effectiveness of night ventilation might be underestimated so far. And the occupant's influence on night ventilation might not be as strong as during the day, as it is merely a reaction to a ventilation policy and the security properties of the façade.

As key drivers for occupants using night ventilation, field studies identified indoor temperature [24,19] outdoor temperature [19,22] as well as window state before departure [11,24].

Improvement of night ventilation could therefore be related to the design of small, burglary- (and animal intrusion) free, as well as weather-protected ventilation openings, which do not necessarily

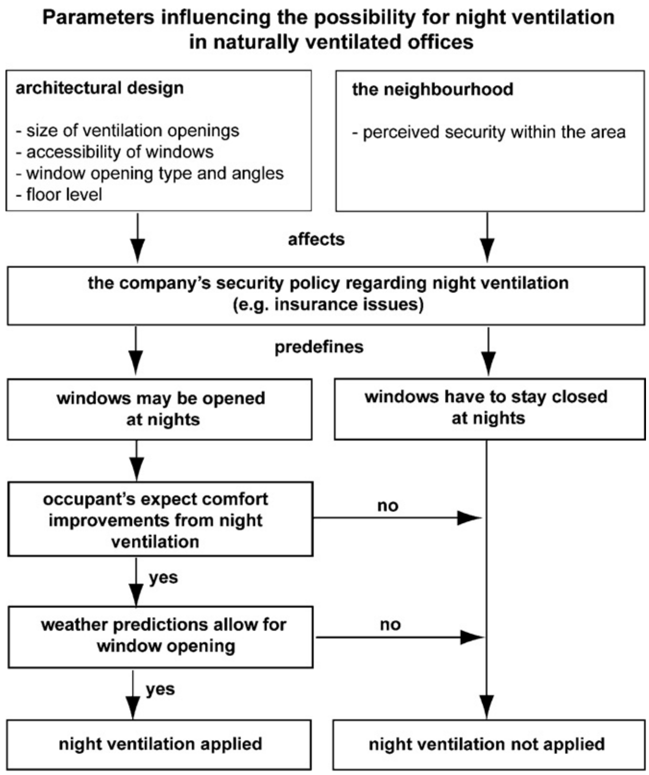


Fig. 11. Hierarchical scheme of parameters influencing whether or not night ventilation might be possible.

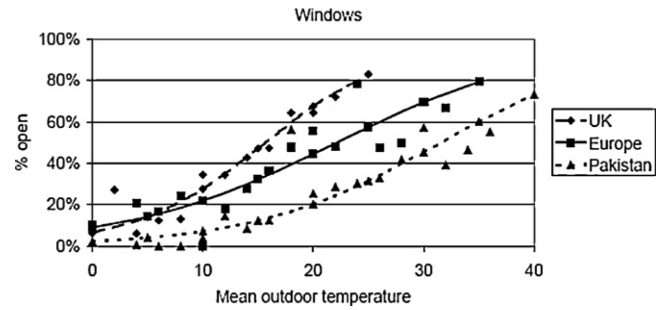


Fig. 12. proportion of windows open at different outdoor temperatures [26]. *Source*: Nicol.

have to be windows. This might also have positive effect on resulting security policies in companies.

Fig. 11 illustrates the hierarchical interactions of parameters influencing the possibility for night ventilation in naturally ventilated offices.

5. Behavioural models for window switching

Regarding window opening behaviour of occupants, most field surveys showed a large individual spread. Nevertheless some conclusions can be drawn:

During heating period, the main reason for window opening seems to be the occupant's desire for fresh air. A second reason, depending on the installed heating system, might be the option to cool room temperatures more quickly than with thermostatic valves [10]. Window closing in contrast seems to be mainly a reaction to prevent cold air entering the room. Therefore it can be concluded that due to larger temperature differences between room and outside air temperature in winter, windows are open for shorter periods. That means that during winter, window opening behaviour is less likely to be influenced by other parameters like outside noise or draft, because the opening periods might already be reduced to the necessary minimum.

During non-heating period there seem to be two main reasons for window openings: the desire for fresh air, and the occupant's wish to cool the room or prevent a further increase of room temperatures. Which one is predominating might vary individually from one building or room to another, mainly depending on the prevailing solar (façade design/window area) and internal heat loads as well as the perceived room air quality. The main reason for closing the windows again during summer, especially in warm climates, seems to be the protection against heat in case the outside air temperature is exceeding the indoor temperature. In case of window opening for cooling or overheating prevention, window opening periods might be longer than would be needed only for the provision of fresh air. This leads to the conclusion that the likelihood of other parameters (outside noise, draft) to influence the occupant behaviour might be higher than during heating period.

Based on field investigations, several models have been developed in order to describe window switching behaviour and to implement it into building simulation:

- Fritsch et al. [10] carried out a field study in offices in Lausanne, Switzerland. Based on these data they developed a stochastic model of the window opening angle, depending on time of the day, outdoor temperature and preceding window angle (Table 2). According to the authors, this model is only applicable in winter and should not be used to model window opening behaviour in summer.
- Based on a database from field studies of subjective comfort in offices in different climates, Nicol [26] proposed an algorithm calculating the probability for window openings as a function of outdoor temperature as shown in Fig. 12.
- Rijal et al. [21,23] used data collected in thermal comfort surveys in 15 office buildings in UK during 18 months to develop the "Humphreys adaptive algorithm", describing the window opening probability as a function of indoor and outdoor temperature.
- Haldi and Robinson [28] conducted a field survey in several nonair-conditioned office buildings in Switzerland during summer and developed a window opening algorithm based on occupancy, time of the day, window opening status, occurrence of rain, as well as outdoor and indoor temperature as shown in Fig. 13.

Table 2
Procedure for the generation of synthetic time series of window angle. *Source*: Fritsch et al. [10].

Steps	Operations
#1	Check the time, if it is not in the office hours the window is closed and go to #5
#2	Choose a Markow matrix according to the outdoor temperature
#3	Build the distribution function from a line of the matrix (# of tie line corresponds to # of precedent class of the window angle)
#4	Generate a new realisation for the window position for the next half hour
#5	Memorise the window position or window angle class
#6	Start in #1 for the next half hour.

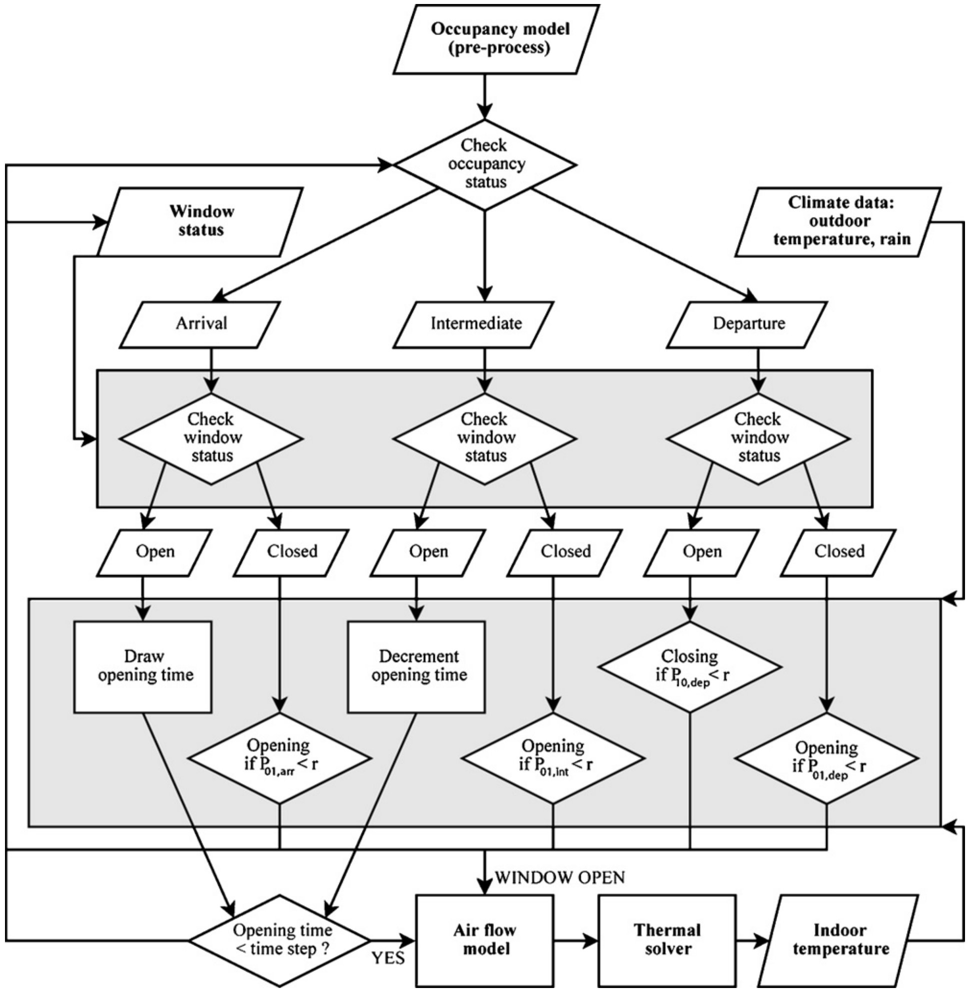


Fig. 13. Implementation scheme of the window opening algorithm. *Source*: Haldi and Robinson [28].

- Yun and Steemers [24] carried out a field study in Cambridge, UK during summer and developed stochastic models to predict window opening behaviour patterns as a function of indoor temperature, time of day and the previous window state (Table 3).
- Herkel et al. [17] conducted a field study in Freiburg, Germany during a period of 13 months. They proposed a user model for prediction of the window status based on occupancy depending on the time of the day and outdoor temperature (Fig. 14).
- Based on a year round field investigation of the use of building controls in 33 Pakistani offices, Rijal et al. [22] developed an adaptive algorithm for window switching as a function of operative, outside air/comfort temperature and the preceding window status.
- Page [29] developed a stochastic model of window opening depending on indoor pollution, indoor temperature and outdoor temperature as shown in Fig. 15.
- Based on a field study, Yun et al. [30] developed a combined algorithm of probabilistic occupant behaviour and deterministic heat and mass balance models, depending on time of the day, occupant type (active, medium and passive), and previous window state (Fig. 16).
- Another control strategy for natural ventilation, although more related to a ventilation system rather than openable windows was proposed by Martin [31]. It is based on the assumption that ventilation is either triggered by room temperature (cooling) or by CO_2 concentration in the room. This model takes wind speed, direction, rain intensity and external temperatures into account.

6. Comfort temperatures depending on perceived levels of control

The occupant's control over operable windows and the resulting ventilation effectiveness has significant impact on the

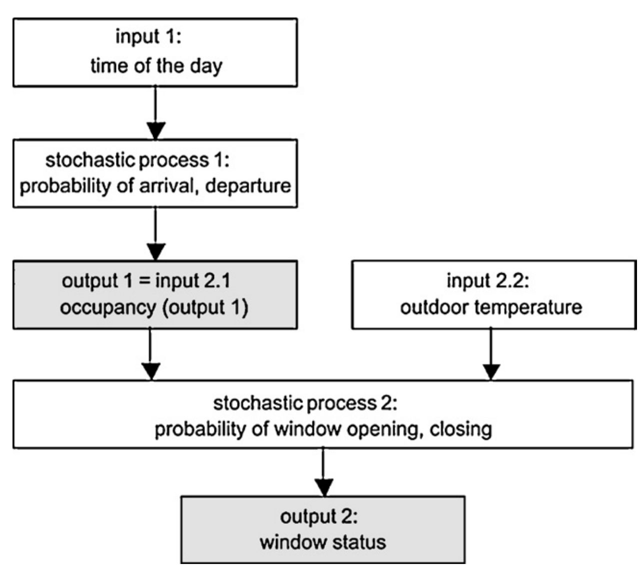


Fig. 14. scheme of the two stochastic processes used to predict the window status [17]. *Source*: Herkel et al.

Table 3
Descriptions of the probability models derived from the field study [24]. *Source*: Yun and Steemers [24].

	Abbreviations	Time of day	Window state		Comparison
			Previous	Current	
Office without night ventilation	$P_{C-O(Arr)}$	Arrival	Closed	Open	$P_{C-C(Arr)} = 1 - P_{C-O(Arr)}$
	$P_{C-O(Int)}$	Intermittent	Closed	Open	$P_{C-C(Int)} = 1 - P_{C-O(Int)}$
	$P_{O-C(Int)}$	Intermittent	Open	Closed	$P_{O-O(Int)} = 1 - P_{O-C(Int)}$
Office with night ventilation	$P_{C-O(Arr)}$	Arrival	Closed	Open	$P_{C-C(Arr)} = 1 - P_{C-O(Arr)}$
	$P_{O-O(Int)}$	Intermittent	Open	Open	$P_{O-O(Int)} = 1 - P_{O-C(Int)}$
	$P_{O-C(Dep)}$	Departure	Open	Closed	$P_{O-C(Int)} = 1 - P_{O-O(Int)}$

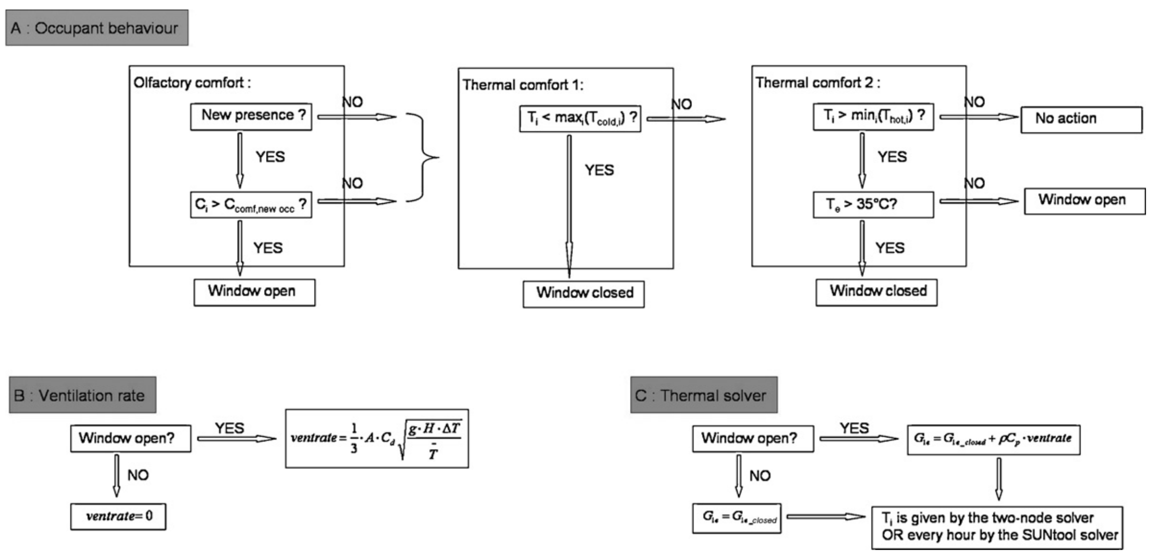


Fig. 15. Actions taking place at each (5 min) time step of the window model. *Source*: Page [29].

perceived thermal comfort sensation. Brager et al. [32] conducted a field study in a naturally ventilated office building in summer and reported a higher neutral temperature of subjects who have higher control over operable windows (e.g. workplace closer to the façade), compared to occupants with minimal control. Additionally this higher neutral temperature more closely approximated the level of warmth at their workplaces, although the thermal environment as well as CLO and MET were similar to the subjects with low control levels.

These findings are supported by Haldi and Robinson [25]. They also noticed an increase of comfort temperature with increasing control of occupants. This was observed for window controls, but the same effect also occurred with other controls like blinds, fans, doors, drinks, activity and clothing. Additionally, the more of these different controls were provided, the higher was the observed comfort temperature.

7. Discussion and conclusions

According to IPCC, the building sector provides the largest potential to mitigate the climate change. The European Energy Performance of Buildings Directive [1] therefore aims to reduce the energy consumption for heating, cooling and lighting in buildings. All member countries are asked to transpose these requirements into national legislation, and to provide a suitable theoretical calculation/evaluation method for the energy performance.

Nevertheless there are often large deviations between theoretically calculated- and measured energy performance and comfort in buildings.

One main reason for these differences is the fact that these theoretical calculation procedures are mainly based on physical variables or average values. As such, they do not account for occupant behaviour or characteristics of the local climate or the specific building. But as the literature review revealed, these aspects are crucial for calculation procedures or building simulation in order to achieve realistic results. The following paragraph examines possibilities to implement characteristics of climate and occupant controlled ventilation into building simulation.

7.1. Climate data

Concerning the climate, calculation methods prescribed by national regulations and building simulation often refer to standard weather data, for example test reference years. These data lack some important information: they do not reflect the range of typical summer conditions that can occur within a decade. While in 1 year there might be an extremely hot summer, it might be average in another year. Additionally the frequency and intensity of heat waves might vary from 1 year to another. All these variations have significant influence on the effectiveness of natural ventilation and the resulting thermal comfort in a building. For this reason the choice of weather data is important when using building simulation [33]. With weather data generators it might be possible to create data which are closer to reality than test reference years. But further research/measurements will be needed to provide weather data for use in building simulation, corresponding to real measured summer conditions including extreme climatic events like heat waves.

Another climatic aspect influencing the discrepancy between calculated and measured building performance is the heat island effect. It can strongly influence the effectiveness of natural ventilation, but is depending on the individual characteristics of

A combined behaviour algorithm

Stage 1: Initialisation

i. Set initial window state: $\theta^{(1)} = \lambda = 0$

Stage 2: Trial State

i. Choose a new trial state: ϕ where $\phi \in S = \{Closed, Open\} = \{0,1\}$

Stage 3: Transition Probability

i. Calculate the probability of the state changing to ϕ : $P^{(i)}(\phi)$

Stage 4: Evaluation

i. Generate random variable: $U \sim U[0,1]$

ii. Compare $P^{(i)}(\phi)$ with U

- if $P^{(i)}(\phi) \geq U$ then, accept the trial state ϕ
- if $P^{(i)}(\phi) < U$ then, reject the trial state ϕ

iii. Set the state of Markov chain at simulation time step i: $\theta^{(i)}$

- if the change is accepted, set $\theta^{(i)} \leftarrow \phi$
- if the change is rejected, set $\theta^{(i)} \leftarrow \theta^{(i-1)}$

Stage 5: Computation

i. Solve thermal and mass balance equations

Stage 6: Internal Repetition

i. Repeat from Stages 2 to 5 until it reaches the last simulation time step

Stage 7: Iteration

i. Repeat Stage 6 until it satisfies the predefined Monte Carlo iteration number

Fig. 16. Diagram of the Yun algorithm. *Source*: Yun et al. [30].

the specific urban canyon. Even measured weather data for the same location are usually measured at the nearest meteorological station. This is typically an airport outside the city, where the heat island effect does not occur. Further research/measurements will be needed to provide climate data including the effect of heat islands in urban environments.

Generally it is suggested to use different weather data in building simulation to show the range of influence of annual changes as well as urban microclimate might have at a specific location. These data should ideally be based on measured weather data of the last decade (Table 4).

7.2. Occupant control of ventilation openings

Concerning natural ventilation, regulations for energy performance evaluation often assume constant ventilation rates. However, field studies on window switching behaviour showed, that occupant controlled ventilation is influenced by a variety of parameters, and the resulting air exchange rates are therefore constantly changing.

Table 4
Proposed weather data sets for a specific location to be used for building simulation, considering annual changes and local microclimate.

Category I: annual changes	Subcategory: local microclimate
1. Average year (based on measured data of the last decade)	1a. Location outside a city 1b. Inner city location (incl. heat island effect)
2. Hot year (based on measured data of the last decade, including heat waves)	2a. Location outside the city 2b. Inner city location (incl. heat island effect)

Several behavioural models have been developed, to predict occupant controlled ventilation through openable windows more precisely. They predict windows to be either opened or closed. As such they better reflect window opening types providing either an opened or closed position. For steplessly adjustable window opening types, they do not provide information regarding changing opening percentages/angles with time. Nevertheless this would have important influence on the resulting ventilation rates. Therefore the applicability of window switching models for different window opening types should be further investigated.

Additionally, these behavioural models do not reflect the whole range of parameters influencing occupant ventilation. Many of these parameters are related to façade design like window size, shape and location within the façade, window opening type and opening angels/percentages and the influence of shading devices. But there are also other influences, referring to the individual characteristics of the indoor and exterior environment, like indoor air quality, placement of furniture, outside air quality and noise. All those parameters are very specific and strongly depending on the characteristics of an individual building. And many of those parameters might not yet be known in early design stages. However, energy performance calculations based on national regulations as well as building simulations are often performed in early design stages in order to get the building permission. For this reason, although window opening models might predict window opening more precisely than standard assumptions for ventilation rates, there might still be significant deviations between real and predicted occupant behaviour for ventilation.

Generally it can be concluded, that comfort and energy performance calculations/simulations which do not take the occupant behaviour into account might therefore be a source of error. However, almost all field studies observed a large individual spread of different occupant behaviour even under similar circumstances.

For this reason it might be useful to demonstrate the range of influence of possible occupant ventilation control on energy performance and comfort in a building rather than trying to predict it precisely. This range could be defined by simulating the best as well as the worst case scenario of occupant behaviour regarding energy performance and/or comfort. The real behaviour will then be somewhere in between those boundaries, and might change according to individual characteristics and preferences or with tenant changes. This approach might reflect real user behaviour better than precise models, because it implies the uncertainty which will always remain when aiming to predict human behaviour. Since this approach is not aiming to make any precise predictions on occupant behaviour, the methods to define the best and the worst case scenario of behaviour can be more generalized, too. As such, occupant behaviour could not only be considered in specific building simulation software like ESP-r [34] or Trnsys [35], but also in simple simulation tools and in calculation methods according to energy regulations like EPBD. This would offer the possibility to account for the influence of user behaviour on natural ventilation even in early design stages. Further research will be needed to define the best- and worst case scenario for occupant controlled ventilation.

Generally architects/engineers and clients should agree at the beginning of the optimization of project about the desired adaptive thermal comfort level inside the building, and the summer characteristics when this comfort level should be maintained. Additionally the uncertainties of the results due to individual characteristics of occupant behaviour should be discussed.

7.3. Adaptive thermal comfort

Many field studies observed that occupants in naturally ventilated buildings prefer higher room temperatures in summer than their counterparts in air-conditioned buildings. This effect can be explained by higher levels of personal control provided by naturally ventilated buildings, i.e. the possibility to manually control ventilation by opening or closing the windows [32]. This adaptive opportunity is considered in adaptive thermal comfort standards like Ashrae Standard 55 [36], EN 15251 [37] or ISSO 74 [38], providing different comfort evaluation methods for naturally ventilated and air-conditioned buildings.

However, literature review shows that occupant control of natural ventilation is depending on a variety of influences. And the occupant's perceived control might not only depend on the presence of openable windows, but also on other parameters like window opening type, window size, shape and placement, the question how many persons control how many windows, the accessibility of the windows (placement of furniture) or the hierarchical relation to colleagues in case of shared control over the windows. Those parameters also influence the effectiveness of natural ventilation. An optimized configuration might, apart from increasing perceived control, also increase the ventilation rates. And thus, the amount of working hours with satisfying thermal comfort might be increased as well. Further research would be needed to investigate in the effect of optimized ventilation controls on adaptive thermal comfort.

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